Moving beyond the MSY concept to reflect multidimensional fisheries management objectives

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Abstract

Maximising the long term average catch of single stock fisheries as prescribed by the globally-legislated MSY objective is unlikely to ensure ecosystem, economic, social and governance sustainability unless an effort is made to explicitly include these considerations. The study investigated how objectives to be maximised can be combined with sustainability constraints aiming specifically at one or more of these four sustainability pillars. It was conducted as a three-year interactive process involving 290 participating science, industry, NGO and management representatives from six different European regions. Economic considerations and inclusive governance were generally preferred as the key objectives to be maximised in complex fisheries, recognising that ecosystem, social and governance constraints are key aspects of sustainability in all regions. Relative preferences differed between regions and cases but were similar across a series of workshops, different levels of information provided and the form of elicitation methods used as long as major shifts in context or stakeholder composition did not occur. Maximising inclusiveness in governance, particularly the inclusiveness of affected stakeholders, was highly preferred by participants across the project. This suggests that advice incorporating flexibility in the interpretation of objectives to leave room for meaningful inclusiveness in decision-making processes is likely to be a prerequisite for stakeholder buy-in to management decisions.

Key words: Sustainability pillars, Inclusive governance, MSY, MEY, MSOY, management objectives,

1. Introduction

The definition and use of long term targets and limits for fisheries management is at the heart of fisheries science. Defining these is in essence a policy decision and some, such as the Maximum Sustainable Yield (MSY) (UNCLOS 1982), have attained global support. MSY refers to the maximisation of the long-term average landed weight, generally using a specific fishing rate or effort management rule. The concept was originally developed on a single stock basis, and does not explicitly encompass sustainability in wider ecosystem, economic, social and governance contexts (Anderson *et al*., 2015; Hilborn *et al*., 2015; Prellezo and Curtin, 2015; Rindorf *et al*., 2017a). In such multidimensional settings, there are trade-offs between objectives such as catches of predators and their prey (Legovic *et al*., 2010; Blanchard *et al*., 2014), catches of individual species caught in mixed fisheries (Dichmont *et al*., 2008; Hilborn *et al*., 2012; Ulrich *et al*., 2017), long term average yield and stability of yield (Smith *et al*., 2011), and economic yield and social factors such as employment (Kempf *et al*., 2016). Deciding on these trade-offs is an integral part of defining broader strategic objectives for ecosystem based fisheries management (Garcia *et al*., 2003).

In jurisdictions where advice has moved beyond the objective of obtaining single species MSY, this has been implemented by, for example, defining limits to fishing on all species to ensure MSY of the least productive species (in the US, Hilborn *et al*., 2015) or by estimating the maximum economic yield, MEY, across all species (Australia, Dichmont *et al*., 2010). Other objectives, such as maximising the added value to consumers while ensuring acceptable employment levels, have also been suggested (Methot *et al*., 2014). Often, potential objectives are defined in scoping exercises involving scientists, managers and other stakeholders, followed by model analyses of the likely consequences of different management measures for performance metrics related to the objectives (Mapstone *et al*., 2008; Punt et al., 2016; Punt, 2017). The complexity of this decision process can be greatly decreased if the number of trade-offs which need to decided on can be reduced. Further, complexity and duration of the process is highly dependent on the preferences for different objectives expressed by the stakeholders included in the process being both broadly representative of other stakeholders and reasonably stable over time as the development of model scenarios and subsequent discussions take time to complete.

The aim of this study was to investigate how ecological, economic, social, and governmental fisheries management objectives can be consistently addressed in MSY advice. To this aim, the manuscript describes a process through which the most appropriate trade-off can be determined in any specific case and then investigates whether this process provides results which are consistent over time and stakeholder groups. Part of the process is to limit the trade-off area to only those options considered most relevant by stakeholders, as reducing the number of options that must be considered greatly reduces the complexity of the trade-offs to be considered. Specifically, it was investigated i) whether objectives related to ecosystem, economic, social and governance issues should preferably be addressed as objectives to be maximised or as constraints to be avoided in sustainable management, ii) how the list of objectives and constraints can be limited to reduce the complexity of subsequent discussions by using preferences, iii) whether preferences varied between regions and stakeholder groups, and iv) whether preferences derived using a different method, context and level of detail of the information given were broadly similar to the original scoping exercise. The investigation was based on a three-year study involving scientists, industry, NGOs and managers to investigate preferences in different regions, in different stakeholder groups, in different contexts and based on different levels of detail. The study concludes by discussing the implications of the results for future science, advice and management.

2. Materials and methods

While the widely used MSY and MEY concepts suit single species management objectives, the goal of maximsing rarely suits objectives related to multiple and diverse ecosystem, economic, social and governance indicators. Principles such as those of sustainable development (WCED

1987) are often seen as higher ranking, leading to a situation where objectives maximising for example, yield are not acceptable if they jeopardise sustainability (EU, 2013; Hart, 2013; Rindorf *et al.*, 2017b). Objectives were defined as being related to sustainability where specific ecosystem aspects (such as maintaining forage species and minimising bycatch mortality of potentially endangered or threatened species), economic aspects (such as profitability of fisheries), social aspects (such as employment in the fishery) and governance aspects (such as participation in the decision process) are managed to remain within acceptable limits. The dimensions identifying the limits to this sustainable area were denoted constraints, and objectives for maximisation were discussed only within the sustainable area.

2.1 Consultation

The process of consulting and discussing options with stakeholders occurred in three stages aiming at the four scientific aims (i to iv in the introduction):

- A problem framing workshop defining preferred objectives and constraints among categories by region to determine whether preferences differed across regional groups,
- Subsequent reflection workshops to derive perspectives from different stakeholder groups and more detail on preferred objectives, and lastly
- Response workshops to determine whether the objectives originally identified were still seen as relevant when presented to a broader stakeholder group using a different method, context and level of detail of the information given.

In all workshops, stakeholders were identified as scientists, industry, NGOs, or managers depending on their employer (Figure 1).

Figure 1 about here

2.2 Regional differences in preference

The 55 participants in the problem framing workshop conducted in April 2012 were invited partners in the MYFISH project (www.myfishproject.eu) or members of organisations associated with the project, including regional advisory councils from all regions, industry representatives, NGOs and managers (Figure 1). Invitations were sent to each organisation and the organisation then selected the most appropriate available attendees. The majority of the organisations were European but participants from New Zealand, Canada and the US were also present. Workshop topic groups focused on identifying a range of potentially relevant objectives and constraints related to alternatives to MSY. The preference for each of these was subsequently ranked on a regional basis in groups encompassing the Baltic Sea, Mediterranean, North Sea, Western Waters and Widely Ranging Stocks, where the latter covers migratory as well as distant water fisheries. Details of the process can be found in the supplementary information. A specially designed graphical tool was used to facilitate option ranking and recording (Kempf *et a*l., 2016, supplementary material). The tool listed the suggested objectives to be considered for maximisation (or minimisation in one case) and the sustainability constraints to that objective derived from the topic groups. Participants were asked to provide ratings (R) for each option and to document the degree of uncertainty or disagreement in the group (U) after group deliberation. Ratings and uncertainty were evaluated following three criteria: i) availability of necessary information, ii) responsiveness of the measure to management, and iii) preference as an objective to maximise or as a sustainability constraint. Priority was given to rating objectives considered for maximisation and, if time permitted, potential constraints to sustainability were also ranked. All groups evaluated objectives at the meeting but constraints were evaluated by only three groups. Remaining constraint evaluations were carried out using questionnaires completed by participants at a later date. This led to a systematic scoring and ranking of options based on the agreed assessment by all the workshop participants. Lastly, the options with the highest preferences were identified for each regional group together with the degree of agreement among regional groups, and the overall ranking. The probability for each category of obtaining the observed number of top 5 rankings was estimated using a binomial probability.

2.3 Perspectives from different stakeholder groups

The results of the problem framing workshop were presented at two reflection workshops in October 2012 and in February 2013, both with a higher representation of managers than the initial workshop (Figure 1) and both focusing on the Baltic Sea, North Sea and Widely Ranging Stocks. Participants were invited through ICES, regional Advisory Councils and among European and national managers. The workshops were structured as plenary discussions on whether the definitions and preferences indicated in the problem framing workshop seemed appropriate and operational, and on how the objective to maximise inclusive governance (see section 3.1) could be implemented in practice. Views of the participants were gathered in a workshop report by a core group of scientists and the report was circulated to participants for comments.

2.4 Changes in preferences in response to context and the level of information

The effect of including a broader stakeholder group and using a different method, context and level of detail of the information given was investigated in six regional response workshops conducted in 2014 (Figure 1). The context of the response workshops differed from the original workshop as a broader range of stakeholders were involved, new key issues to stakeholders had emerged in the two years since the initial problem framing and reflection workshops, quantitative information on the potential trade-offs resulting from the previously expressed preferences was presented, and finally, the consultation method was changed to individual questionnaires. Participants were invited through Advisory Councils and local stakeholder organisations.

Detailed information on the consequences of choosing a specific target, or sets of targets, and management constraints was produced for each of six regions using quantitative statistical models where possible and qualitative models where quantitative models were not available (Voss *et al.*, 2014a; Kempf *et al.*, 2016; Quetglas *et al.*, 2016; Sampedro *et al.*, 2017; García *et* *al*., 2017). The resulting trade-offs between different ecosystem, economic and social consequences were illustrated using decision support tables (DST) (Kempf *et al*., 2016). These DSTs visualised model results using graphical tools, such as icon arrays, and were accompanied by a brief description of the model used to derive the underlying data. They included examples of different versions of objectives and constraints.

Preferences were indicated by participants using individual questionnaires, which were completed at the meeting. This approach was used in response to comments at previous workshops that group interactions might affect the results. The questionnaires asked participants to indicate their preferences for each of the scenarios presented (rating, 5 point scale) and how certain they were about their rating (uncertainty; 4 point scale). Finally, there was opportunity for them to give the main reasons for their ratings in free text format on the questionnaire. To enhance comparability with results from the problem framing workshop, the questionnaires were analysed by taking the rating and uncertainty score of individual answers, converting them to distributions approximating the discrete distributions used in the problem framing workshop and then pooling these into a single distribution representing the group similar to those derived in the problem framing workshop. Further details on the workshops can be found in the supplementary material and details on the objectives and constraints rated are given in Tables 1 and 2.

Tables 1 and 2 about here

3. Results

3.1 Regional differences in preference

The full list of possible objectives to maximise and sustainability constraints was used for all regional workshops. Suggested objectives and constraints were categorised into the four pillars of ecosystem, economic, social and governance sustainability (Tables 1 and 2). For both objectives and constraints, the social component had the highest number of proposed options. Average and variation of both rating and uncertainty varied between groups, indicating that a ranking method was preferable to ANOVA or similar analyses.

Social yield was suggested to be difficult to quantify and therefore better addressed through negotiations or constraints rather than maximisation of specific measures. Indicators of stability and resilience were also seen as important constraints in conjunction with other indicators rather than as objectives to be maximised. Some terms were context specific, such as the meaning of 'long term'. In ecosystem considerations, 100 years was considered appropriate, whereas in an economic and social science context much shorter periods were considered long term. Further, stakeholders generally expressed a need to discuss both `Where to go in the long term?' and `How to get there in the shorter term?'.

3.1.1 Objectives for maximisation

All but six of the indicators were ranked as good or very good by at least one group (Figure 2). The six objectives which ranked as medium or poorer in all regional groups were: Maximise Community Biomass, Maximise Resilience, Maximise Employment on Viable Fishing Units, Maximise Fishing Community Viability, Maximise Social Yield and Maximise Present Yield for Human Consumption. Among the ecosystem and economic objectives, all groups except Widely Ranging Stocks preferred maximising yield in value (economic) to maximising yield in tonnes (ecosystem). Maximise value landed came in the top five ranked of all regions (Table 3) except the Baltic Sea and Widely Ranging Stocks where it was ranked sixth and eighth, respectively.

There was a high preference across all regions for economic and governance objectives for maximisation while the social category received poorer ratings (Figure 3). Maximise Inclusive Governance was always highly rated by the groups scoring this objective and economic objectives were in the top 5 in four of the five regions (Table 3, Figure 2). With the exception of the Mediterranean, at least one social objective was present in the top 5 in all regions, but the specific objective differed between groups.

Figure 2 and 3 and table 3 about here

Maximise Inclusive Governance, Yield in Value of Key Commercial Species and Yield in Tonnes of Key Commercial Species showed high agreement in scoring between groups with scores of Yield in Value being consistently better than those of Yield in Tonnes in all groups except the Widely Ranging Stocks group. The objectives Minimise Risk of Falling Outside Constraints, Maximise Resource Rent, Maximise Willingness to Invest in Future Fisheries, Maximise Stability, Maximise Employment on Viable Fishing Units, Maximise Catch in Tonnes, Maximise Consumer Welfare and Happiness, and Maximise Fishery Welfare and Happiness showed large differences between regions (Figure 2). Of these, Maximise Resource Rent and Maximise Catch in Tonnes showed the largest difference, both being scored as the highest ranking by one group and lowest by another group.

3.1.2 Constraints to sustainability

There were substantial differences between regions on which constraints were preferred (Table 4). In the North Sea and Widely Ranging Stocks the focus was on Good Environmental Status of commercial species, biodiversity, food web functioning and seafloor integrity, and areas with fishing restrictions. While indicators of ecosystem constraints also appeared in the Mediterranean, they were much more dominant in the North Sea and Widely Ranging Stocks where 7 of 12 possible top 5 constraints were related to ecosystems compared to just two of 11 for the Mediterranean. None of the social constraints listed in the Baltic Sea, North Sea and Widely Ranging Stocks regions referred to issues such as small community viability, employment or subsidies. However, such constraints were prioritised highly in the two Mediterranean cases.

Only one economic constraint was mentioned in the top five of any region (profits – Mediterranean Sea). Overall, the economic constraints featured relatively less in the top 5 preferred list than in the list of potential constraints (Figure 4, table 5). Further, there was a higher proportion of constraints related to governance in the preferred list compared to the full list (Figure 4, Table 5).

Table 4 and 5 and figure 4 about here

3.2 Perspectives from different stakeholder groups

The first reflection workshop focused on the main priorities for scientific advice on objectives and constraints. The workshop participants felt that scientific advice should recommend ecosystem limits for sustainable exploitation (constraints) on a stock by stock basis. Additionally, participants stated that it was necessary to illustrate the consequences of choices for a wider set of management objectives and that more detailed information on trade-offs would also be useful. Receiving single point advice for all stocks based on, for example, an economic objective was not considered to provide sufficient room for negotiation. Instead, participants preferred to be informed about those trade-offs that fell within the sustainable area. Some participants expressed a preference for limiting the scope of the trade-off scenarios considered solely to those that were sustainable in a single stock and ecosystem context, or would provide solutions that were close to single stock based MSY reference values. Within this 'sustainable and close to objective' range, there could be room for considering other issues, for example negotiations or an inclusive process. Current legislation and governance was seen as an important constraint. The full report is given in ICES (2012).

At the second reflection workshop, the participants concluded that advice should ensure single stock sustainability. Broadly, their conclusions matched those of the previous workshop:

participants felt that the role of the scientists was to advise on trade-offs between different objectives within the sustainable range and not to determine the exact management measures to be implemented, stating the importance of governance aspects. It was not considered to be the role of scientists to determine the exact trade-offs against, say, economic objectives, although such information can be presented to inform the decision making process. The full report is given in Rindorf *et al*. (2013).

3.3 Consistency in preferences

There was a high correspondence between the initially preferred objectives and constraints and the preferred options in a later context, where more detailed information was provided to a broader group of stakeholders in a later context, in all but two cases (Baltic Sea and Western Waters)(Table 6). While the Baltic Sea workshop showed the same trend as the initial analysis, the response workshop showed only very minor differences in preference between different options. This was presumably linked to the recent collapse of the stock assessment of Baltic cod, which initiated in-depth discussions of the relevance of the quantitative information. In the Western Waters, relative representation by different stakeholder groups was important as representatives of artisanal fleets preferred to be outside the TAC and quota management system and maintain their effort regardless of the objective used to manage the entire fishery. They had no favoured objectives beyond the social constraint to retain status quo effort and employment, while the industrial fleet representatives preferred MEY. As the artisanal fleet representatives were absent in the problem framing workshop, this dichotomy was new to the response meeting. For all objectives, the issues of how the path towards reaching objectives should be designed and the time frame within which this should be achieved were general concerns. At the problem framing workshop, three of the four preferred objectives in the Western Waters group included aspects of fleet economics (Maximise Yield in Value of Key Commercial Species, Maximise Yield in Value, and Maximise Willingness to Invest in Future

Fisheries), though Maximise Net Present Value was not among the highest rated indicating a change between the two workshops. An additional comment made at several of the workshop was that even when only the most preferred objectives and constraints were presented, the information presented was highly complex and no single option seemed to satisfy all preferences.

Table 6 about here

4. Discussion

Through the process implemented in the three workshops, the participants constructed a list of potential ecosystem, economic, social and governance objectives and constraints, many of which address the shortcomings of the current insular, single-species, single discipline definitions of MSY, while retaining the concept of objectives that are to be maximised within sustainability constraints. Economic objectives were preferred among objectives to be maximised, but were selected less when determining sustainability constraints. Social objectives were given less weight among objectives to maximise. However, the main observation was the overwhelming importance of governance variables, including process attributes, in both objectives and constraints. Preferences for objectives and constraints appeared stable as context, composition of the group and information level changed, except in the case where the stakeholders originally consulted excluded specific groups and in the case where the stock assessment for a major species had suddenly changed dramatically.

Preference was higher for the maximisation of economic objectives compared to maximisation of ecosystem objectives in four of the five regions and no social objective was consistently preferred for maximisation. In contrast, economic constraints were substantially less frequent among the preferred constraints than in the full list. Social constraints appeared in the same proportion in the preferred and the full list while ecosystem constraints appeared in substantially higher proportion in the preferred compared to the full list. Hence, both ecosystem and social constraints were seen as key aspects of sustainability that need to be ensured by setting limitations on the objective of maximising economic yield, and thus in effect receiving precedence over objectives related to maximisation. The preference for economic maximisation objectives over ecosystem maximisation objectives was greatest in areas where species interact and/or different species and sizes are caught in the same fishery, such as the Baltic Sea, North Sea and Western Waters. The value lost by maximising ecosystem objectives such as the total catch in tonnes is particularly large in these regions. Two regions, the Baltic Sea and Widely

Ranging Stocks, have historically shown large fluctuations in the size of many stocks and an objective to minimise risk or maximise stability was scored in the top five in both regions. Though indicators of ecosystem constraints appeared in all regions, they dominated lists of northern region groups, while social sustainability constraints were most important in the Mediterranean in accordance with the results of Voss *et al*. (2014b). Maximising Inclusive Governance was highly preferred in all regions where this was evaluated (see also Zeller and Pauly, 2004). Similar emphasis was found in a study from South Africa (Hara, 2013). The lack of support for maximisation of social aspects here and elsewhere (Dichmont *et al*., 2012) may be the result of a lack of history with these indicators, or participants' lack of experience with these concepts (McShane *et al*., 2011; Stephenson *et al*., 2017), or different sectors having differing social objectives. Another important issue is the role of science in the decision making process. Several participants remarked that deciding on social and economic trade-offs should be left to political negotiations and that the role of scientists should be relegated to making the consequences of these decisions explicitly known (Rindorf *et al*., 2017a).

The ranking of different objectives was consistent between the initial problem framing and subsequent response workshops as long as no major shift in stakeholder composition or context occurred. This was unexpected, as it was suggested in the problem framing workshop that social objectives may change quickly compared to biological objectives, particularly in an economic downturn, where the focus is often more on short term economic and social priorities than on long term ecosystem objectives (Mardle and Pascoe, 2002). Though absolute ratings differed substantially between workshops, the relative preferences seemed less affected than absolute level.

While the relative preference for different objectives may remain fairly constant, the management measures required to attain ecosystem objectives will vary over time as fisheries selectivity and stock productivities change (Blenckner *et al*., 2016). Economic objectives such as Maximise Resource Rent reflect changes in both stock productivity and economic factors, such as fuel price, whereas social objectives may reflect economic yield and operational management as well as social aspects such as the distribution of welfare within society or public opinion. Hence, the three types of objectives are likely to be highly interdependent as all depend on stock productivity and current and projected stock status.

There was a clear dichotomy between the strong support for inclusive governance and for addressing shortcomings of single species MSY seen in the problem framing and response workshops, and the preference of managers for limiting the scope of any scenarios considered to those that are sustainable and provide close to MSY in tonnes in a single stock context. This difference of opinion seemed to be caused by the perception of the importance of maintaining consistency with current legislation. For example, fishing above the fishing mortality leading to MSY in a single species context for a species otherwise limiting the economic yield is in direct conflict with legislative requirements in some parts of the world (US, 2007; Fisheries and Aquaculture Law, 2013; EU, 2013; Shelton and Morgan, 2014). While the requirement to remain consistent with current legislation limits the number of practically feasible objectives and constraints, it does not eliminate the need to decide how to address all sustainability pillars in management. In this decision, the need for explicit and clear scientific advice on the consequences of different options remains as does the need for an inclusive process.

The need to remain within sustainable limits received far more support in discussions than maximising any one specific objective. It was stressed in all workshops that objectives should only be maximised when also considering sustainability within ecosystem, economic and social contexts. Examples of the “sustainable area” as being the area where all dimensions of sustainability were fulfilled were often mentioned, even though such an area may not always exist (Rindorf *et al*., 2017a). To facilitate this, most stakeholders opted for the use of ranges rather than point estimates in defining objectives. Providing advice on trade-offs within sustainable ‘objective-ranges’ was seen as a scientific task and policy makers were tasked with deciding on the exact trade-offs to be made within these ranges. The ranges would allow room for discussing economic and social considerations in an inclusive process involving science, industry, NGO and policymaker representatives in an institutionalised format. In Europe, there has been a recent move towards trying to identify objectives as ranges of fishing mortalities providing yields close to MSY (EU, 2014), thereby providing some flexibility in policy decisions (Kempf *et al*., 2016; Rindorf *et al*., 2017b).

The workshop process implemented in this study demonstrated broad support among stakeholders for consistently addressing ecological, economic, social, and governmental fisheries management objectives in MSY advice by defining ecosystem and social constraints to management within which yield, economic benefits and inclusive governance can be broadly maximised. The importance of ecosystem and social constraints was widely supported by multiple workshop participants and priority should be given to defining operational indicators of ecosystem, social and governance sustainability to operationalise these aspects, a need which is also percieved from a scientific perspective (Stephenson et al. 2017). Preferences for economic objectives differed between complex interacting fisheries, such as those in the Mediterranean and North Sea, and simpler cases, such as the Widely Ranging Stocks. Preferences appeared to be relatively similar across workshop participants, context, level of detail and elicitation methods used as long as no major shifts in context or participant composition occurred. The ubiquity of inclusive governance as a key objective suggests that there is an urgent need to operationalise this concept, so that it can work even in a complex and slowly reacting management system like the European system (Eliasen *et al*., 2015). Involving stakeholders in defining objectives and management choices is essential to achieve consensus, buy-in and compliance (Pascoe *et al*., 2009; Wilson, 2009). Advice that incorporates MSY and MEY concepts into more flexible decision-making frameworks so as to leave room for inclusiveness is likely to be a prerequisite for effective management.

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6. Supplementary material

Workshop process, initial problem framing workshop

In the first part of the problem framing workshop, participants were divided into four different topic groups according to their stated individual preferences to identify possible objectives and constraints. Each group focused on one of the following: ecosystem issues, stock interaction issues, economic issues and social and governance issues. In the topic groups different objectives for maximisation were discussed and a consensus was reached on those to be evaluated further. The number of participants in the groups ranged from 11 to 18. Scientists tended to join the group covering their area of expertise. NGOs were only represented in the groups on ecosystem issues and stock interaction issues. Industry representatives were present in all groups but mostly attended the economic and social and governance groups. The groups were asked to focus on three questions: ‘What can/should we maximise?’, ‘What should we sustain?’ and ‘How can we implement it?’.

The second part of the initial problem framing workshop determined which objectives and constraints were considered relevant and desirable in different regions. This was conducted in regional groups encompassing the Baltic Sea, Mediterranean, North Sea, Western Waters and Widely Ranging Stocks, where the latter covers migratory as well as distant water fisheries.

A graphical tool recorded and displayed the distribution of ratings (see example in Figure S1). Evaluations were based on a five point scale from “very good” to “very poor”, and uncertainty or disagreement within the group was reflected in a distribution of scores. Group rapporteurs included text comments in the spreadsheets explaining group decisions. The ratings were integrated into a distribution of “utility” for each objective and constraint using a matrix method. The matrix method operates on discrete distributions in a way that is mathematically consistent with an intuitive interpretation of how distributions should be related. For example, ‘low’ feasibility and ‘low’ impact should lead to a distribution for the utility probability mass concentrated around the ‘low’ end of the scale. The method is described fully in Holt et al.

(2014). The options were subsequently ranked primarily on expected utility values with uncertainty as a secondary ranking criterion, if utility values were the same.

Figure S1 about here

Description of regional response workshops

Baltic Sea

Baltic Sea stakeholders were consulted through the Baltic Sea Advisory Council, at a workshop in June 2014 (Figure 1). The effects on yield and ecological, economic and social sustainability of three different objectives were demonstrated in a DST: Maximise Net Present Value (Economic), Maximise Net Present Value While Conserving Sprat (Economic with ecosystem constraints) and Maximise Net Present Value While Conserving Equity between Countries (Economic with social constraints).

Eastern Mediterranean: Aegean Sea

Scenarios for the Aegean Sea were presented and discussed during the annual meeting of the Pan-Hellenic Union of Middle-Range Ship Owners in June 2014 (Figure 1). The series of objectives examined included the current single species MSY (Ecosystem), Maximise Net Present Value (Economic) and a scenario which went towards MEY but limited the reduction of fleet capacity (Economic with social constraints).

Western Mediterranean: Balearic Sea

A workshop was organized in January 2014 with the participation of fishermen and representatives from fisheries managers (Figure 1). The set of objectives examined included the current fishing exploitation scheme, Maximise Net Present Value (Economic) and an intermediate scenario in between these two previous, extreme situations in which the effort, catch and economic value are at the average between the current and the predicted MEY scenarios (Economic with social constraints).

North Sea

The stakeholder workshop for the North Sea case study was held in July 2014 together with the North Sea Advisory Council demersal fisheries group (Figure 1). Three different cases were discussed. The first focused on biological interactions in the context of multispecies MSY in tonnes (Ecosystem), value (Economic) and multispecies ranges (Ecosystem and Governance). The second focused on MSY in tonnes (Ecosystem) and net present value (Economic) when accounting for technical interactions in the fisheries on North Sea gadoids while implementing single species F_{MSY} and a landing obligation. The third focused on multispecies MSY in tonnes (Ecosystem) and net present value (Economic) for flatfish and shrimp fleets in the southern North Sea in an ecosystem setting.

Western Waters

The stakeholder workshop was held for the Iberian Sea case study in conjunction with a regular meeting of the South Western Waters Advisory Council in June 2014 (Figure 1). Two objectives were presented, single stock MSY (Ecosystem) and Maximise Net Present Value of key commercial species (Economic). These two objectives were combined in scenarios with constant effort in artisanal fleets, as a proxy for maintaining the employment in these fleets (adding social constraints).

Widely Ranging

A stakeholder workshop was organized in February 2014 together with the Pelagic Advisory Council (Figure 1). Two issues played a large role at the workshop: firstly, an important ad-hoc meeting on Mackerel TAC distribution was scheduled just prior to the workshop resulting in a lower attendance of industry members and secondly, the interpretation of MSY under a landing obligation varied considerably among participants. Case-studies focused on Norwegian Spring Spawning herring, North Sea herring and North Sea sprat and tuna in the Indian Ocean. Results for MSY (Ecosystem), Stability of Catches (Ecosystem) and Good Environmental Status of the stocks (Ecosystem) were presented for the North Sea stocks. Alternatives for Tuna in the Indian Ocean were presented at an IOTC meeting in November 2014 where mixed-fisheries MSY was the main point of discussion.

7. Figure captions

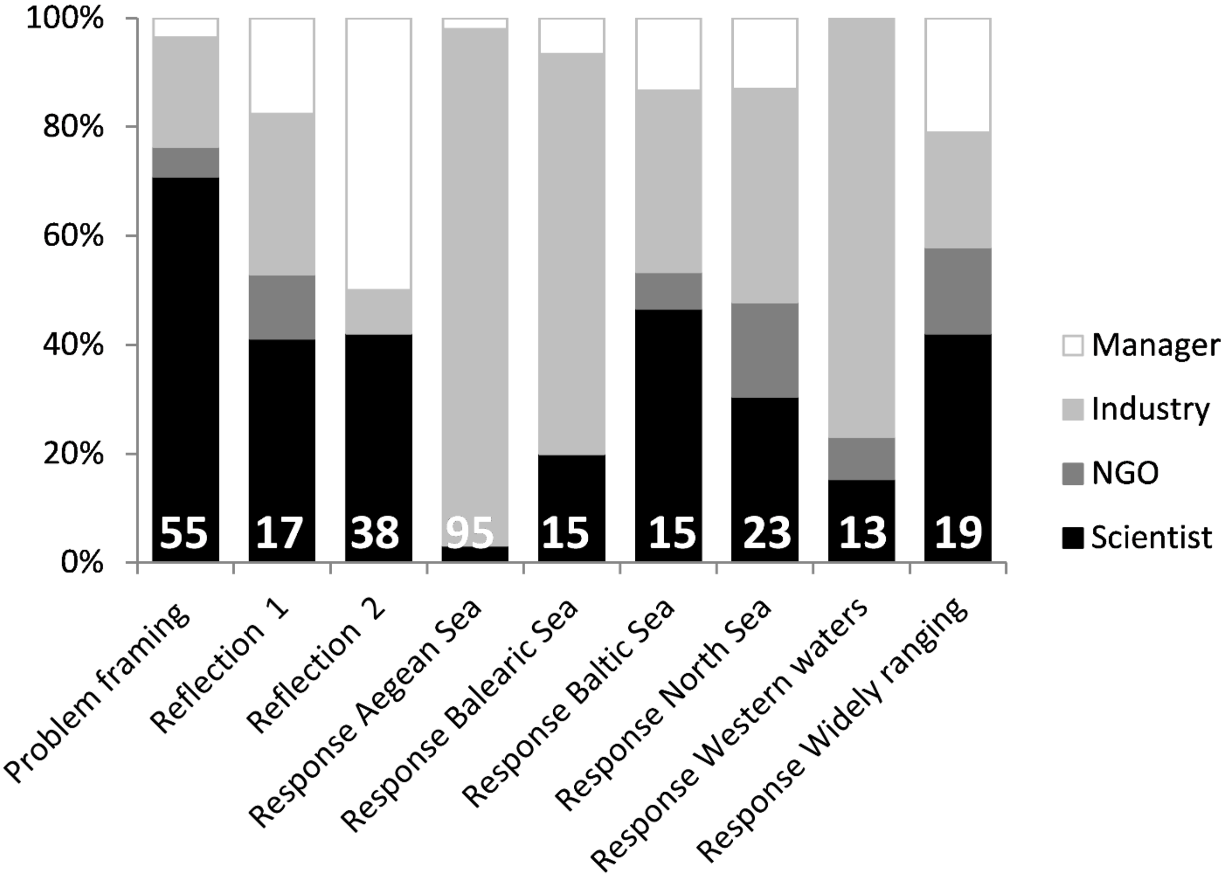
Figure 1. Total (number) and composition (bars) of participants in the workshops.

Figure 2. Graphic summary of overall average means and range of means for different objectives by different regional groups. Objectives that were evaluated by fewer than three regional groups are not included.

Figure 3. Average rating of objectives in the different categories by regional groups ordered from no interaction (left) to high interaction (right) between yields of different fisheries. Bars indicate rating average and vertical lines show the range of ratings observed in that category.

Figure 4. Distribution of objectives to be maximised and constraints to limit sustainability across sustainability pillars on the full list (options) and the top five selected in regional groups.

Figure S1. Graphical tool to record ratings. Four evaluations are shown. The bottom right panel represents medium desirability with high uncertainty or disagreement. For the other panels, the evaluation ranges from “very good” (top left), “medium” (top right), to “very poor” (bottom left), each with very little uncertainty or disagreement


100%
80%
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55
17
38
95
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15
23
13
19
Manager
Industry
NGO
Scientist
Problem framing
Reflection 1
Reflection 2
Response Aegean Sea
Response Balearic Sea
Response Baltic Sea
Response North Sea
Response Western waters
Response Widely ranging

Fig.1

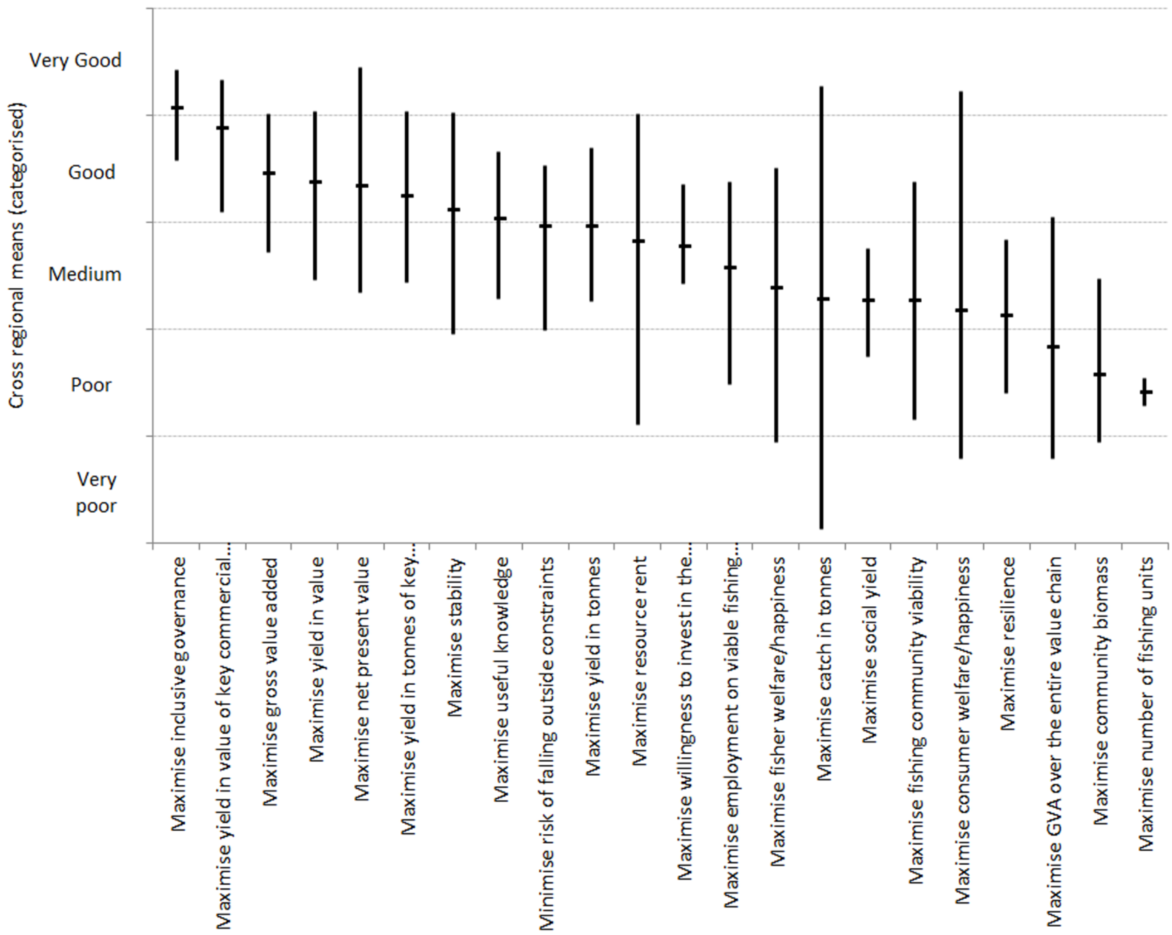

Very Good
Good
Medium
Poor
Very poor
Cross regional means (categorised)
Maximise inclusive governance
Maximise yield in value of key commercial…
Maximise gross value added
Maximise yield in value
Maximise net present value
Maximise yield in tonnes of key…
Maximise stability
Maximise useful knowledge
Minimise risk of falling outside constraints
Maximise yield in tonnes
Maximise resource rent
Maximise willingness to invest in the…
Maximise employment on viable fishing…
Maximise fisher welfare/happiness
Maximise catch in tonnes
Maximise social yield
Maximise fishing community viability
Maximise consumer welfare/happiness
Maximise resilience
Maximise GVA over the entire value chain
Maximise community biomass
Maximise number of fishing units

Fig. 2

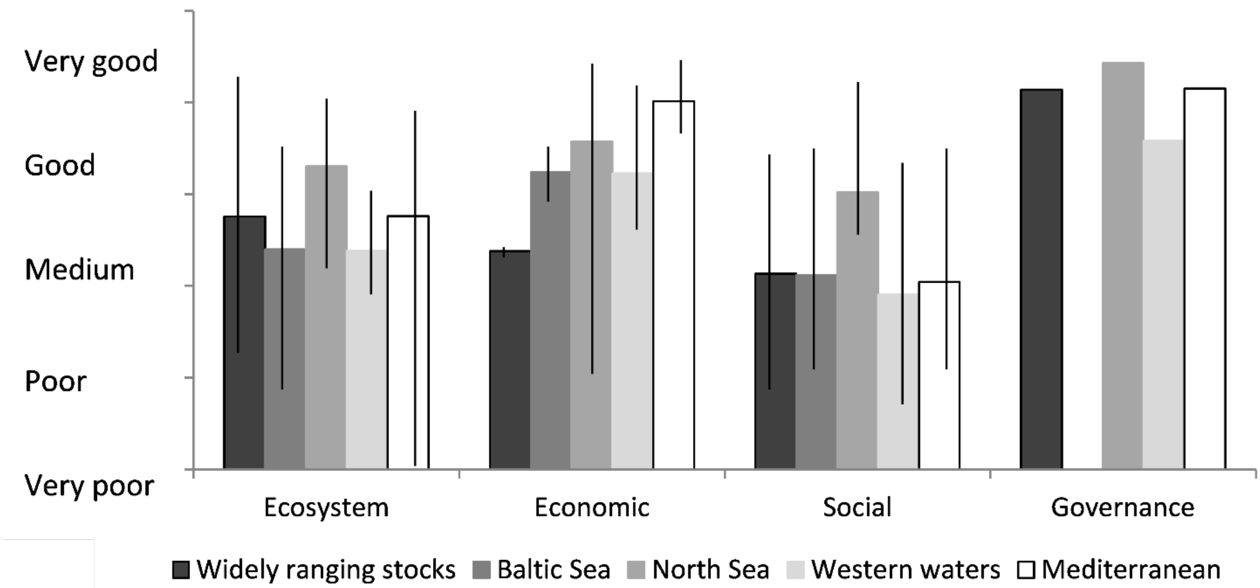

Very good
Good
Medium
Poor
Very poor
Ecosystem
Economic
Social
Governance
Widely ranging stocks
Baltic Sea
North Sea
Western waters
Mediterranean

Fig. 3

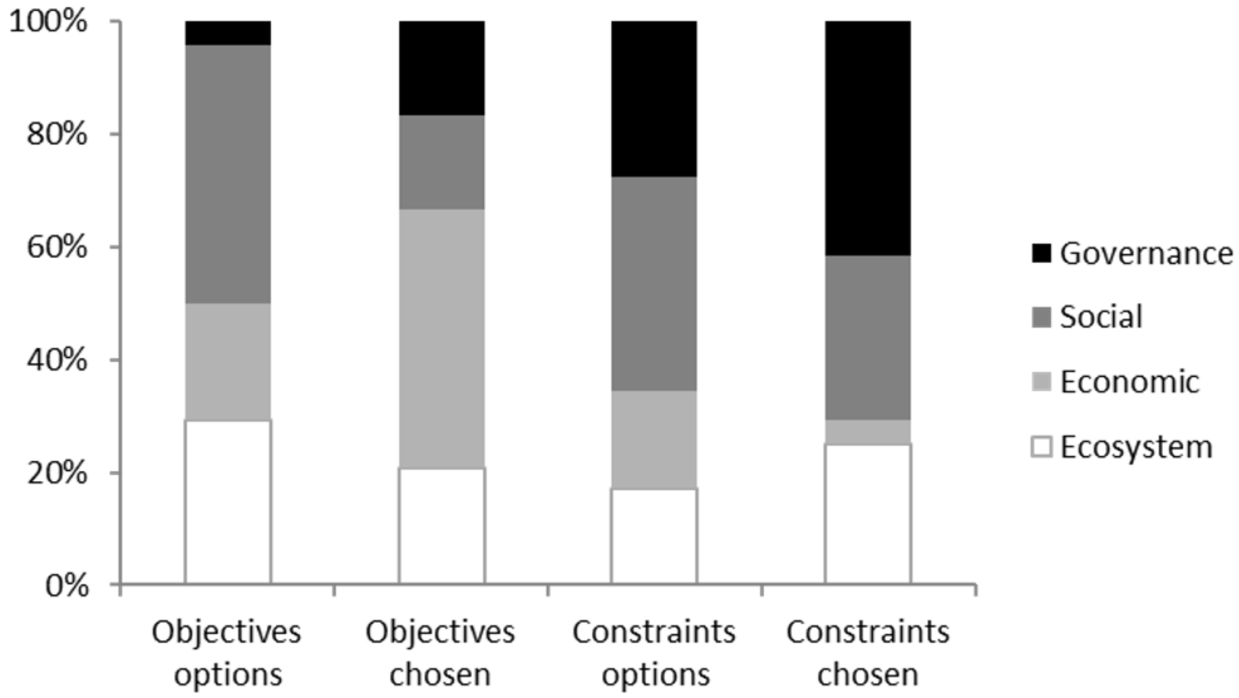
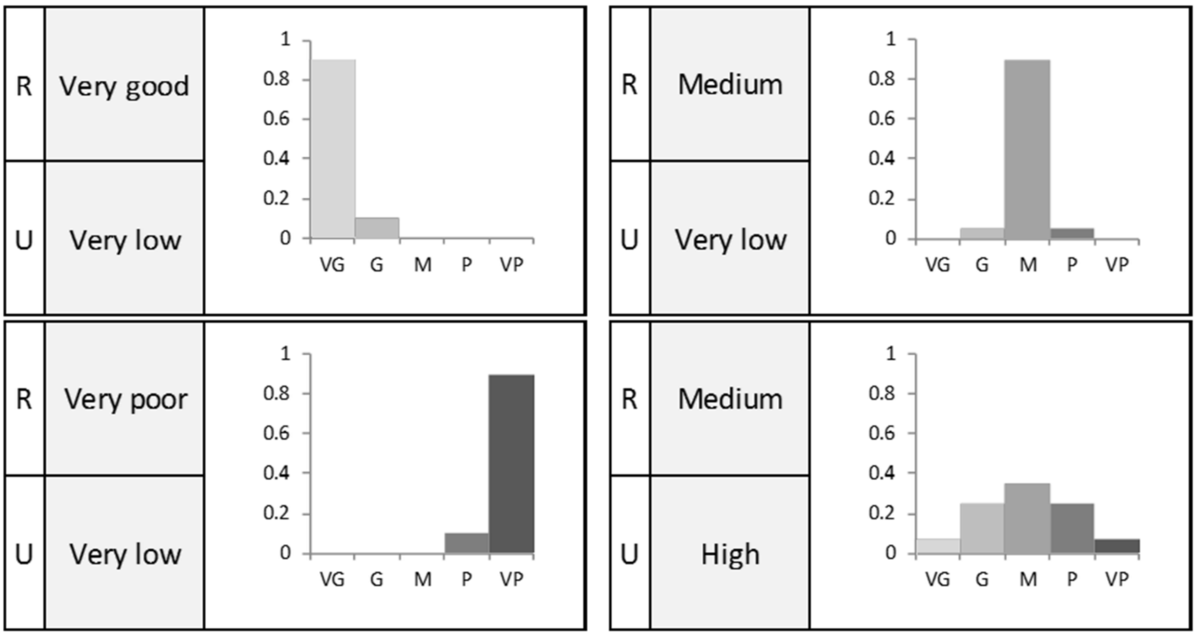

100%
80%
60%
40%
20%
0%
Objectives options
Objectives chosen
Constraints options
Constraints chosen
Governance
Social
Economic
Ecosystem

Fig. 4


R
Very good
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High
VG
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M
P
VP

Fig S1

Table 1. Potential objectives to maximise (or minimise) identified in the problem framing workshop.

Option	Category	Explanation
Maximise Yield in Tonnes	Ecosystem	Summed weight of landings of all commercial species
Maximise Yield in Tonnes of Key Commercial Species	Ecosystem	Summed weight of landings of key commercial species
Maximise Catch in Tonnes	Ecosystem	Summed weight of catch (including discards) of all commercial species
Maximise Present Yield for Human Consumption	Ecosystem	Summed landings used for human consumption
Maximise Stability	Ecosystem	Stability in landings or catches
Maximise Community Biomass	Ecosystem	Summed biomass in the ecosystem
Minimise Risk of Falling Outside Constraints	Ecosystem	Constraints are boundaries beyond which management is considered unsustainable
Maximise Resilience	Ecosystem	The ability of the ecosystem to absorb pressures without creating permanent distortion
Maximise Yield in Value of Key Commercial Species	Economic	Summed value of landings of key commercial species
Maximise Yield in Value	Economic	Summed value of landings of all commercial species
Maximise Gross Value Added	Economic	Summed value of landings less all variable costs
Maximise Resource Rent	Economic	Summed surplus value less all costs and normal returns
Maximise Net Present Value	Economic	Summed value of landings less all costs discounted back to its present value
Maximise Yield/Litre of Fuel or CO_2 Emission	Economic	This objective includes aspects of both MEY (maximise yield/variable cost) and MSOY as CO_2 was also suggested as an example of a societal cost
Maximise Number of Fishing Units	Social	
Maximise Fisher Welfare/Happiness	Social	
Maximise Consumer Welfare/Happiness	Social	
Maximise Willingness to Invest in the Future Fisheries	Social	
Maximise Social Yield	Social	Summed value from a societal perspective in 4x4 categories: Utility, Experimental, Future, Institutional value from a social, cultural, governance, ecological perspective
Maximise Employment on Viable Fishing Units	Social	Requires a definition of ‘viable’
Maximise Gross Value Added over the Entire Value Chain	Social	Summed value of fish/invertebrate products less all variable costs in fishing and processing
Maximise Fishing Community Viability	Social	Requires a definition of ‘viability’
Maximise Health Benefit/CO_2	Social	Health benefit could be essential fatty acids and CO_2 was given as an example of a societal cost
Maximise Useful Knowledge	Social	
Maximise Inclusive Governance	Governance	Engaging an appropriate range of stakeholders to influence the decision-making process. The range of stakeholders should include all categories of stakeholders and the process should be iterative.

Table 2. Potential constraints to sustainability identified in the initial Problem Framing workshop.

Option	Category
Indicators of Good Environmental Status of commercial species, biodiversity, food web functioning and seafloor integrity above reference level	Ecosystem
Mortality of potentially endangered and threatened species and other vulnerable species below specified level	Ecosystem
Profits above a minimum level	Economic
Technical selectivity unaltered	Economic
Reduce barriers to mobility in the fishing industry (to join or leave the industry)	Economic
Meet certification requirements	Economic
Stability of landings	Social
Discard of non-target species below specified level	Social
Carbon footprint less than specified level	Social
Maintain human food supply above specified level	Social
Legislation adhered to/compliance above reference levels	Social
Maintaining small communities at a specified level	Social
Maintaining vessel size distribution at a certain level	Social
Human accidents at sea below a specified level	Social
Employment above a specified level	Social
Equity of income	Social
Increase status of fishers	Social
Maintain consumer choice for different kinds and sources of fish	Social
Management cost below specified level of GVA	Governance
Retain subsidies	Governance
Maintain trust among industry participants	Governance
Increase level of self-determination for fishing actions by fishers	Governance
Maintain fishing rights and ownership	Governance
Maintain relative stability[1]	Governance
Legislation adhered to/compliance	Governance
Areas with fishing restriction (e.g. Natura 2000)	Governance

[1]See Hoefnagel et al. 2015 for definition.

Table 3. Top five ranked objectives for maximisation (or minimisation) for all regions where these received 'Good' or 'Very good' ratings. Ratings are: < 0.8: Very good; 0.8-1.4: Good.

Region	Objective	Ranking	Rating	Category
Baltic Sea	Minimise Risk of Falling Outside Constraints	1	1.17	Ecosystem
Baltic Sea	Maximise Gross Value Added	1	1.17	Economic
Baltic Sea	Maximise Resource Rent	1	1.17	Economic
Baltic Sea	Maximise Fisher Welfare/Happiness	3	1.19	Social
Mediterranean Sea	Maximise Net Present Value	1	0.44	Economic
Mediterranean Sea	Maximise Inclusive Governance	2	0.68	Governance
Mediterranean Sea	Maximise Gross Value Added	3	0.79	Economic
Mediterranean Sea	Maximise Resource Rent	3	0.79	Economic
Mediterranean Sea	Maximise Yield in Tonnes of Key Commercial Species	5	0.87	Ecosystem
Mediterranean Sea	Maximise Yield in Value of Key Commercial Species	5	0.87	Economic
North Sea	Maximise Inclusive Governance	1	0.46	Governance
North Sea	Maximise Yield of Fish/Litre of Fuel (or CO_2 Emission) or similar energy unit	2	0.47	Economic
North Sea	Maximise Yield in Value of Key Commercial Species	3	0.53	Economic
North Sea	Maximise Consumer Welfare/Happiness	4	0.62	Social
North Sea	Maximise Yield in Value	5	0.77	Economic
Western Waters	Maximise Yield in Value of Key Commercial Species	1	0.65	Economic
Western Waters	Maximise Yield in Value	2	1.12	Economic
Western Waters	Maximise Inclusive Governance	3	1.14	Governance
Western Waters	Maximise Willingness to Invest in the Future Fisheries	4	1.32	Social
Widely Ranging Stocks	Maximise Catch in Tonnes	1	0.58	Ecosystem
Widely Ranging Stocks	Maximise Inclusive Governance	2	0.69	Governance
Widely Ranging Stocks	Maximise Stability in catches	3	0.92	Ecosystem
Widely Ranging Stocks	Maximise Yield in Tonnes	4	1.04	Ecosystem
Widely Ranging Stocks	Maximise Useful Knowledge	5	1.25	Social

Table 4. Top five ranked sustainability constraints.

Region	Constraint	Ranking	Category
Aegean Sea (Mediterranean)	Employment Above a Specified Level	1	Social
Aegean Sea (Mediterranean)	GES Descriptors of Commercial Species Above Reference Level	2	Ecosystem
Aegean Sea (Mediterranean)	Maintaining Small Communities at a Specified Level	3	Social
Aegean Sea (Mediterranean)	Retain Subsidies	4	Governance
Aegean Sea (Mediterranean)	Legislation Adhered To/Compliance	5	Social
Balearic Sea (Mediterranean)	Areas with Fishing Restriction (e.g. Natura 2000)	1	Governance
Balearic Sea (Mediterranean)	Profits Above a Minimum Level	2	Economic
Balearic Sea (Mediterranean)	Employment Above a Specified Level	2	Social
Balearic Sea (Mediterranean)	Retain Subsidies	2	Governance
Balearic Sea (Mediterranean)	Maintaining Small Communities at a Specified Level	2	Social
Balearic Sea (Mediterranean)	Stability of Landings	2	Social
Balearic Sea (Mediterranean)	Maintain Human Food Supply Above Specified Level	2	Social
North Sea	GES Descriptors of Commercial Species, Biodiversity, Food Web Functioning and Seafloor Integrity Above Reference Level	1	Ecosystem
North Sea	Areas with Fishing Restriction (e.g. Natura 2000)	1	Governance
North Sea	Mortality of PET and Other Vulnerable Species Below Specified Level	1	Ecosystem
North Sea	Discards of Non-target Species Below Specified level	1	Ecosystem
North Sea	Legislation Adhered To/Compliance	1	Governance
North Sea	Maintain Relative Stability	1	Governance
North Sea	Human Accidents at Sea Below a Specified Level	1	Social
Widely Ranging Stocks	GES Descriptors of Commercial Species Above Reference Level	1	Ecosystem
Widely Ranging Stocks	Mortality of PET and Other Vulnerable Species Below Specified Level	2	Ecosystem
Widely Ranging Stocks	Areas with Fishing Restriction (e.g. Natura 2000)	3	Ecosystem
Widely Ranging Stocks	Maintain Trust Among Industry Participants	4	Governance
Widely Ranging Stocks	Maintain Relative Stability	5	Governance

Table 5. Proportion of objectives in the preferred top five relative to the maximum possible, and the proportionexpected if no selection took place.

Category	Ecosystem	Economic	Social	Governance
Proportion of possible objectives	0.29	0.21	0.46	0.03
Proportion of rated objectives in top 5[*]	0.21 (P=0.1250)	**0.46 (P=0.0041)**	**0.17 (P=0.0020)**	**1.00 (P<0.0001)**
Proportion of possible objectives	0.17	0.17	0.38	0.28
Proportion of rated objectives in top 5[*]	0.25 (P=0.1052)	0.04 (P=0.0639)	0.29 (P=0.2535)	**0.42 (P=0.0427)**

[*]relative to the maximum possible, hence these values do not sum to one, as governance had only one objective and this was only rated by four groups (maximum number of top five entries=4).

Table 6. The objectives and constraints evaluated in regional response workshops.

Region	Objectives and constraints presented	Results
Baltic Sea	Maximise Net Present Value (Economic); Maximise Net Present Value While Conserving Sprat (Economic with ecosystem constraints); and Maximise Net Present Value While Conserving Equity between Countries (Economic with social constraints)	The conservation approach (Economic with ecosystem constraints) received the best average score (Medium) and showed the lowest variation between participants. This scenario combines aspects of minimise risk and maximises gross value added/resource rent which were originally rated in top 5. However, the differences between the different scenarios were slight, and no strong preferences were observed.
Mediterranean: Aegean Sea	Current single species MSY (Ecosystem); Maximise Net Present Value (Economic); and a scenario which went towards MEY but limited the reduction of fleet capacity (Economic with social constraints)	The preferred scenario was intermediate between single species MSY and MEY. This scenario combines economic objectives to be maximised (net present value) with social constraints (limit change in employment) and the need to Maximise Inclusive Governance, all of which were in the original top 5.
Mediterranean: Balearic Sea	Current fishing exploitation scheme; Maximise Net Present Value (Economic); and an intermediate scenario in between these two extreme situations in which the effort, catch and economic value are at the average between the current and the predicted MEY scenarios (Economic with social constraints)	The preferred scenario was intermediate between the current situation and the full MEY. This intermediate scenario combines the objectives of net present value (Economic) and Maximise Inclusive Governance (Governance), both of which were in the original top 5.
North Sea	1. Focus on biological interactions in the context of multispecies MSY in tonnes (Ecosystem), value (Economic) and multispecies ranges (Ecosystem and Governance) 2. Focus on MSY in tonnes (Ecosystem) and net present value (Economic) when accounting for technical interactions in the fisheries on North Sea gadoids while implementing single species F_{MSY} and a landing obligation 3. Focus on multispecies MSY in tonnes (Ecosystem) and net present value (Economic) for flatfish and shrimp fleets in the southern North Sea in an ecosystem setting	1. The preferred objective was a qualitative approach to multispecies MSY as this approach makes it possible to address with trade-offs caused by biological and technical interactions. The approach combines ecosystem objectives with governance objectives (Maximise Inclusive Governance) and constraints (adhere to current legislation on MSY), both of which were in the original top 5. 2. and 3. The preferred objective was economic objectives (MEY) but concerns about social consequences (i.e. employment) when aiming for MEY were raised. All: The preferred scenarios combined economic objectives (Maximise value landed or Yield per Litre Fuel) and governance objectives (Maximise Inclusive Governance), all of which were in the original top 5, in solutions where ranges in acceptable yield allowed room for negotiation.
Western Waters	Single stock MSY (Ecosystem) and Maximise Net Present Value of key commercial species (Economic) combined in scenarios with constant effort in artisanal fleets, as a proxy for maintaining the employment in these fleets (adding social constraints)	The preferred objectives depended on the stakeholder compositions as representatives of artisanal fleets preferred to be outside the TAC and quota management system and maintain their effort regardless of the objective used to manage the whole fishery. On the other hand, the industrial fleet representatives preferred Maximise Net Present Value of key commercial species (Economic objective), and economic objectives were dominant in the original top 5.
Widely Ranging Stocks	Focus on Norwegian Spring Spawning herring, North Sea herring and North Sea sprat. Results for MSY (Ecosystem), Stability of Catches (Ecosystem) and Good Environmental Status of the stocks (Ecosystem) for the North Sea.	The objective MSY in tonnes while ensuring stability in catches was preferred by most participants (Ecosystem objective with ecosystem constraints). This scenario combined aspects of Maximise Yield in Tonnes, Maximise Stability and Maximise Inclusive Governance, all of which were in the original top 5.

24